TECHNICAL REPORT ARBRL-TR-02578

A STOCHASTIC APPROACH TO VULNERABILITY ASSESSMENT

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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Mean vulnerable area and distribution about the mean is estimated for a small target which has been described using combinatorial geometry. Estimates are made for eight target grid cell sizes and the case with no grid superimposed on the target. Mean vulnerable area versus cell size and spread about the mean are considered. Based on 568 data points per cell size, it is concluded that differences in mean vulnerable area obtained in using a variety of cell sizes or no grid at all are small; but that spreads about the mean, due to the same, vary significantly.

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I. INTRODUCTION

The GIFT (Geometric Information For Targets) and VAST (Vulnerability Analysis for Surface Targets) computer codes are used at the US Army Ballistic Research Laboratory (BRL) in performing vulnerability analyses on a variety of military targets. Details on these codes are documented in a series of reports.[1,2,3]

GIFT superimposes a grid consisting of square cells over the target. The grid is of sufficient size to cover the minimum rectangle in which the target may be enclosed (see Figure 1). Usually, an integral number of cells will not coincide with the minimum rectangle, so that the grid includes cells which extended beyond the edges of the target and its minimum enclosing rectangle. The edge length of the grid cells is chosen by the analyst. After the edge length is set, each cell is automatically divided into one hundred (100) square subcells. GIFT then places a shotline through the center of each cell or through the center of a randomly selected subcell of each cell, as per the analyst's instruction.

The VAST program operates on the GIFT target and shotline compilations in estimating the target vulnerable area. That is to say, each vulnerable area estimate requires a GIFT/VAST computer run combination. Typically, the target to be analyzed requires the use of large amounts of computer time when these programs are employed. In most cases, one run of these programs is made in order to estimate the vulnerable area of the given target. The following questions arise:

(1) How much will the vulnerable area estimate vary over a series of computer runs if the option to place a shotline through randomly chosen subcells is exercized?

(2) If the shotlines are allowed to vary randomly over the entire target instead of within a fixed grid, how will the estimate of vulnerable areas change?

(3) How will vulnerable area estimates change as grid size or number of shotlines is increased or decreased?

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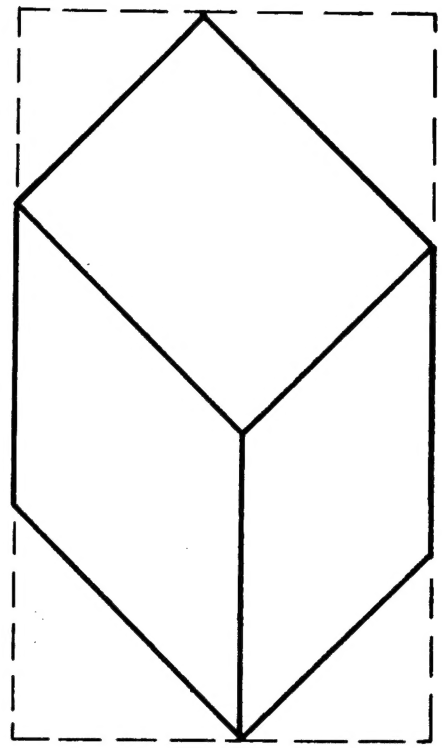
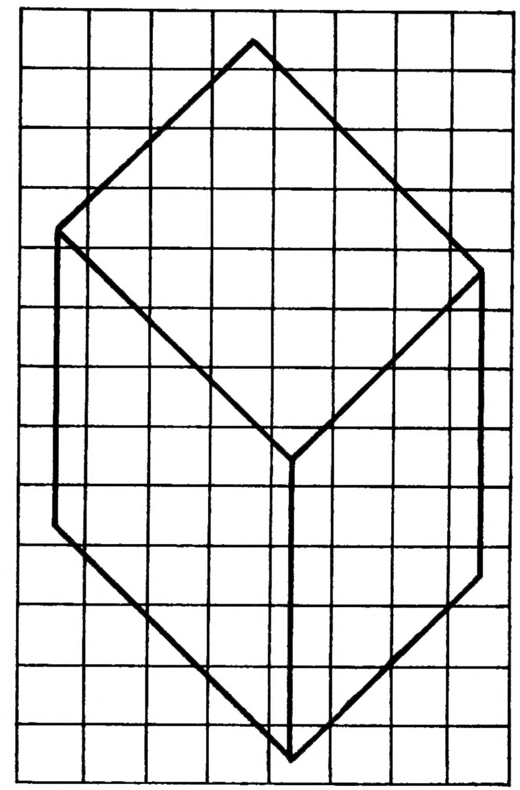
[1] *Lawrence W. Bain, Jr. and Mathew J. Reisinger, "The GIFT Code User Manual; Volume I. Introduction and Input Requirements," US Army Ballistic Research Laboratories Report No. 1802, July 1975. ADB006037*

[2] *Gary G. Kuehl, Lawrence W. Bain, Jr., and Mathew J. Reisinger, "The GIFT Code User Manual; Volume II. The Output Options," US Army Ballistic Research Labortory Technical Report ARBRL-TR-02189, September 1979. ADA078364*

[3] *Thomas F. Hafer and Ann S. Hafer, "Vulnerability Analysis for Surface Targets (VAST), An Internal Point-Burst Vulnerability Model," US Army Ballistic Research Laboratory Technical Report ARBRL-TR-02154, April 1979. ADB0038960*



NO-GRID TARGET IN MINIMUM
ENCLOSING RECTANGLE



TARGET ENCLOSED BY GRID

FIGURE 1. TARGET GEOMETRY FOR 45-DEGREE AZIMUTH AND 30-DEGREE ELEVATION.

In addressing the above questions, several sets of data on estimated target vulnerable area were produced. This was done by altering the GIFT and VAST programs to operate without a grid and modifying GIFT to automatically change its selections of grid subcells through which shotlines were passed, after each run, when a grid was used. The latter change permitted 142 runs to be combined into a single run. Three sets of data resulted from these computer runs. One set of data was in the form of vulnerable area estimates obtained from performing 568 computer runs each, using eight different grid sizes (4, 6, 8, 11, 15, 20, 30, and 60 inches). Another set of data consisted of vulnerable area estimates obtained by allowing one shotline to pass through a random point in the minimum rectangle in which the target could be embedded and replicating this 568 times (no-grid case). See Figure 1. A third set of data was comprised of vulnerable area estimates obtained by averaging areas produced when several shotlines were allowed to pass randomly through the minimum enclosing rectangle on each run. There were 568 groups of 36, 110, and 400 shotlines each. These were selected to match the average shotline density per run of 15-inch, 8-inch, and 4-inch grid cell runs, respectively, in order to be used for comparison. Although single shotline data are not averaged and are, therefore, different kinds of objects from the averaged 36, 110, and 400 shotline data, these two types of data proved to be suitable for comparison. Furthermore, since single shotline data is unaveraged, it is used as a basis for comparison to data obtained from VAST runs using grids. Because of similar shotline density per run, average (36, 110, 400) shotline no-grid data is also compared to data from runs in which a grid is employed. The characteristics of the data which are compared are mean vulnerable area, A_v, and estimated standard deviation, S_{A_v}.

The method used in calculating target vulnerable areas is described below. In the grid case, each shotline is restricted to lie in a given cell and for each cell there corresponds a given shotline. In addition, the vulnerable area is composed of the sum of the vulnerable areas of each cell. Thus, for example, for the 15-inch cell size there are 36 cells and 36 shotlines and each cell has its particular vulnerable area, A_{v_i}. Hence, the vulnerable area of the target is,

$$A_v = A_{v_1} + A_{v_2} + \cdot \cdot \cdot \cdot + A_{v_{36}} \quad . \tag{1}$$

By such a restriction of the location of the shotlines, it is very improbable that a computed vulnerable area is zero, provided the cell size is "small enough".

When a grid is used, each set of components under a cell is assigned a probability of kill given a hit, denoted $P_{K/H}$. The contributions to the vulnerable area made by components under a cell is $P_{K/H}$, times the cell area, times 1 or 0 depending on whether the components under the cell were hit or missed, respectively. Thus, the contributions to the vulnerable area by components under the ith cell is $D_i \cdot P_{K/H_i} \cdot A$, where $D_i = 1$ or 0 as stated above, P_{K/H_i} is the $P_{K/H}$ value of the components under the ith cell, and A is

constant for all cells in the grid and, thus, is not subscripted. It is to be noted that when several components lie under the ith cell, the survivor rule in invoked. The survivor rule works in the following way: let $P'_{K/h_j} = 1 - P_{k/h_j}$ then, $P_{K/H_i} = 1 - \prod_{j=1}^{M} P'_{K/h_j}$, M being the number of components under the ith cell.

The total vulnerable area, A_V, is obtained from the following,

$$A_V = \left[\sum_{i=1}^{N} D_i \cdot P_{K/H_i} \right] A \quad , \tag{2}$$

where N is the number of cells in the grid.

When no grid is used, the vulnerable area is obtained by considering a uniform random hit in the target plane (minimum enclosing rectangle). Although a shotline may be produced through any point on the minimum enclosing rectangle, only one target area is used in determining the vulnerable area. Thus, for a single shotline, the probability of kill is multiplied by the total target area, A_T, to obtain

$$A_V = P_{K/H} \cdot A_T \quad . \tag{3}$$

When N shotlines are produced per GIFT and VAST run, a mean vulnerable area is calculated as,

$$A_V = \frac{A_T}{N} \sum_{i=1}^{N} P_{K/H_i} \quad . \tag{4}$$

The scope of this study did not permit the use of more than one target. The criteria for choosing a target and attack aspect (azimuth and elevation angles relative to a plane parallel to the front face of the target) were: (1) the target should be realistic; (2) the target should be small enough to be subjected to multiple GIFT and VAST computer runs without consuming prohibitive amounts of machine time; (3) the target and attack aspect should produce enough variation in the vulnerable area as shots are taken across the surface to produce useful results. The estimation of the target vulnerable area depends on kill probabilities assigned to target components as well as the precision of the combinatorial geometry description and perhaps other factors. Since criteria 3 could possibly require different attack aspects, two were used: 45-degree azimuth, 30-degree elevation and 0-degree azimuth, 0-degree elevation. The major portion of the data used in this study was derived from the first attack aspect. 0-degree results were similar to those obtained from the oblique attack aspect, except that the ratio of mean vulnerable areas for these two different aspects were not quite proportional to the ratio of their presented areas and likewise for the estimates of their standard deviations. The results and conclusions stated in the remainder of this report are based, essentially, on 45-degree azimuth, 30-degree elevation data.

The target selected is a turbine engine used as a power generator in the Patriot Air Defense System. Its combinatoral geometry description provided for its enclosure in a rectangular cast iron box one-eight inch thick to provide a simulated housing. Its dimensions are 50.0 inches x 43.1 inches. It is a rather symmetrical target.

Attacking fragment masses and velocities chosen for this study were 500, 1000, 2000, and 5000 grains at 3000 and 6000 feet per second for each mass. This, in turn, was reduced to multiple attacks by a 2000-grain fragment striking at 6000 feet per second and two groups of attacks by a 500-grain fragment striking at 3000 feet per second, in order to keep the amount of data to be analyzed within reasonable limits. Except for a somewhat reduced mean vulnerable area, results from 500 grains at 3000 feet per second attacks were the same as those for 2000 grains at 6000 feet per second. The fragment shape factor was 0.01102, typical of 122-mm and 152-mm howitzer rounds. The possibility of spall was disregarded since the engine does not contain much empty space and a simple model was required.

II. RESULTS

Utilizing the option of randomly placing a shotline within a given cell and modifying GIFT and VAST for multiple runs, we have been able to illustrate the variation in calculated vulnerable areas for fixed grid sizes. For each grid size, the vulnerable area has been calculated for a given collection of shotlines and by varying the location of a shotline within its corresponding cell, a sequence of vulnerable areas has been calculated. This computation was repeated 568 times for each cell size and means and standard deviations computed. The results are given in Table 1. The mean vulnerable area, for all cases, is approximately constant; however, the standard deviation increases with increasing cell size. This is depicted in Figure 2, where the standard deviation is plotted versus the number of shotlines used for the corresponding cell size.

In addition, calculations of vulnerable areas were made by using one shotline randomly placed on the target. This was replicated 568 times and a running average of the mean vulnerable area as a function of the replication number or the number of shotlines is given in Figure 3. It is noted that the mean vulnerable area remains between 5.25 and 5.50 square feet for all shots after shot 360. This may indicate a stopping rule. A frequency chart is illustrated in Table 2. One notes immediately the large number of zero-valued vulnerable areas and all non-zero values being grouped between 18.51 and 29.95. This results in a rather imbalanced distribution of vulnerable areas.

By grouping vulnerable area calculations for the no-grid case, we may be able to accomplish the same thing and arrive at a unimodal distribution. Grouping the single-shot, no-grid vulnerable areas, or the shotlines in groups of 36, 110, and 400, we can, for each replication, calculated the mean and standard deviation of the sample. Furthermore, we can obtain the mean and standard deviation of the sampling distribution of the mean. The sample sizes

TABLE 1. TARGET ATTACKED BY 2000 GRAIN MASS AT 6000 FT/SEC, SHOTLINES PASSED THROUGH CELLS OF INDICATED SIZE

Cell Size (Inches)	A_v	S_{A_v}	No. of Runs	Shotlines Per Run	Grid Plane Area (Sq. In.)	Target Area ÷ Grid Plane Area
4	5.52	0.219	566	400	6400	0.6736
6	5.54	0.418	568	182	6552	0.6580
8	5.52	0.697	568	110	7040	0.6124
11	5.43	1.18	568	56	6776	0.6362
15	5.44	1.66	568	36	8100	0.5322
20	5.61	2.70	568	20	8000	0.5389
30	5.37	4.56	568	12	10.800	0.3992
60	5.98	10.1	568	4	14.400	0.2994

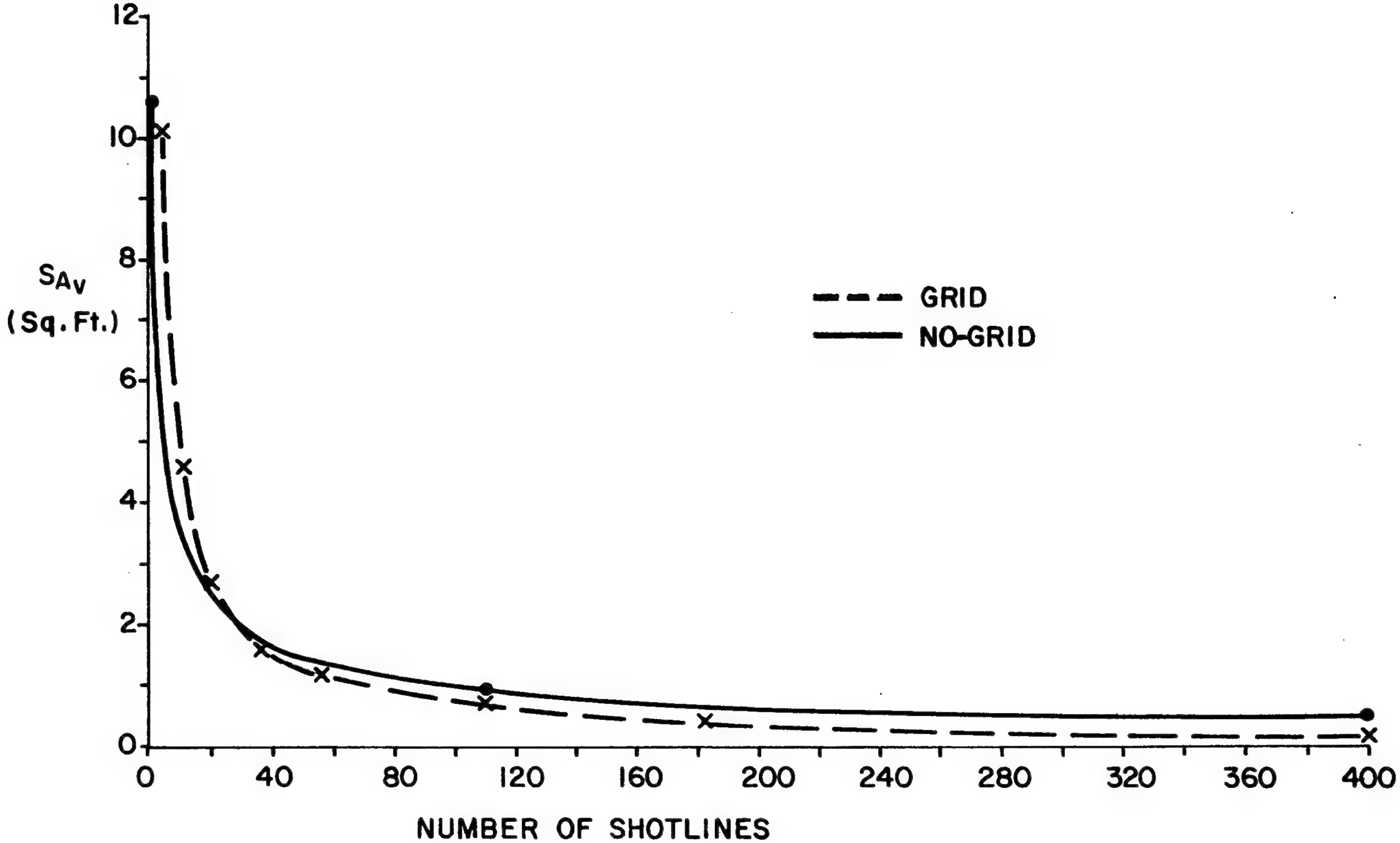


FIGURE 2 . STANDARD DEVIATION VERSUS NUMBER OF SHOTLINES .

FIGURE 3. AVERAGE VULNERABLE AREA, ONE SHOTLINE PER COMPUTER RUN.

TABLE 2. VULNERABLE AREA (A_v) DATA FOR HISTOGRAM OF ONE SHOT, NO-GRID

A_v (Sq. Ft.)	Frequency (f)	A_v as a Percent of Target Area
0	451	0
18.51	1	61.8
23.89	1	79.8
24.11	6	80.5
25.36	14	84.7
25.40	2	84.8
25.52	29	85.2
25.95	50	86.7
27.35	1	91.4
27.35	1	92.0
29.19	1	97.5
29.24	1	97.7
29.25	1	97.7
29.54	1	98.7
29.72	1	99.3
29.85	3	99.7
29.94	2	100.0

Note: $$\frac{\sum f_i A_{v_i}}{\sum f_i} = \frac{3018.75}{568} = 5.31$$

$$\frac{\sum f_i A_{v_i}}{\sum f'_i} = \frac{3018.75}{423} = 7.14 \qquad \left(\begin{array}{l} \sum f'_i = \sum f_i - 145 \\ \text{(delete expected number of misses = 145)} \end{array} \right)$$

$$7.14 \times \frac{\text{Target Area}}{\text{Min. Rect. Area}} = 7.14 \times 0.746 = 5.32$$

36, 110, and 400, were chosen since they correspond to the number of shotlines required for the 15-, 8-, and 4-inch cell sizes, respectively, for the grid case. The mean and standard deviation of the sampling distribution of the mean for the grouped, no-grid case is presented in Table 3, along with the single-shot, no-grid case. In Figure 2, the standard deviation is plotted against the number of shotlines or sample size. In Figure 4, standard deviation times the square root of the sample size (number of shotlines) versus sample size is given for the grid case and the no-grid case. For the no-grid case, the standard deviation times the square root of the sample size is approximately constant, as one would expect; however, this is not true for the grid case. This is probably due to the constrained sampling plan; that is to say, the restriction of shotlines to lie in their corresponding cells rather than a random selection derived over the entire target.

TABLE 3. TARGET ATTACKED FROM 45-DEGREE AZIMUTH AND 30-DEGREE ELEVATION, NO-GRID

Number of Shots Per Run	A_V	S_{A_V}	Number of Runs	$S_{A_V}\sqrt{\text{Number of Shots}}$
1	5.32	10.5	568	10.5
36	5.55	1.69	568	10.2
110	5.53	0.926	568	10.1
400	5.53	0.543	568	10.9

In Figure 5, the histogram of the frequencies of calculated vulnerable areas for the single-shot, no-grid case is plotted; and in Figures 6 through 8, the distribution of the sample mean vulnerable areas are plotted for the 36, 110, and 400 shotlines no-grid cases.

Similarly, the histograms of the calculated vulnerable areas of the 60-, 30-, 20-, 15-, 11-, 8-, 6-, and 4-inch cell sizes have been plotted in Figures 9 through 16. In all cases, it is seen that the mean vulnerable area is relatively insensitive to the grid size used; however, the spread of the calculated areas decreases markedly with decreasing grid size. This has been shown in Figures 2 and 4.

In Table 4, a summary of the mean vulnerable areas has been presented for the cases in which a grid was used. In addition, vulnerable area plus or minus two standard deviations, and the range are displayed. The range is maximum vulnerable area minus minimum vulnerable area. For the case involving no-grid and sampling means, one uses the minimum sample mean vulnerable area and the maximum sample mean vulnerable area, respectively.

TABLE 4. VULNERABLE AREA (A_V) ESTIMATES AND RANGES

Cell Size (Inches)	A_V (Sq. Ft.)	S_{A_V} (Sq. Ft.)	$A_V \pm 2S_{A_V}$ (Sq. Ft.)	Range of A_V Estimates
4	5.52	0.219	5.08, 5.59	4.95 - 6.12
6	5.54	0.418	4.70, 6.38	4.49 - 6.75
8	5.52	0.697	4.13, 6.91	3.67 - 7.19
11	5.43	1.19	3.05, 7.81	2.16 - 9.07
15	5.44	1.67	2.10, 8.78	0 - 11.02
20	5.61	2.70	0.21, 11.01	0 - 14.49
30	5.37	4.56	0, 14.49	0 - 21.58
60	5.98	10.1	0, 26.18	0 - 45.76

Recalling that the mean vulnerable area, as a function of the number of shotlines, remained in the interval 5.25 square feet to 5.50 square feet when the number of shotlines exceeded 360, one can contrast this with the calculated vulnerable area for the 4-inch grid case. In this latter case, the calculated vulnerable area range and the calculated vulnerable area plus or minus two standard deviations is about five to six square feet. For this rather special target and calculation, this is about a possible 20 percent difference or a possible 10 percent difference from the mean.

III. CONCLUSION

The distribution of values of the calculated vulnerable areas for a selection of grid sizes has been calculated by randomly placing a shotline within each cell and replicating this calculation 568 times. For each grid size, the mean and standard deviation have been obtained. For these cases and the cases when no-grid was utilized, we have shown a marked insensitivity of the mean vulnerable area to grid size and to sample size. The spread about the mean or standard deviation grows with grid size or decreased sample size.

The procedures used here suggest the variability inherent in vulnerability estimates but are not recommended for use with general vulnerable area calculations due to time and cost considerations, even though this process is readily implemented. In order to arrive at interval estimates of vulnerable areas, more efficient methods must be investigated, such as the "bootstrap" procedure under investigation by Dr. Malcom Taylor of this laboratory.

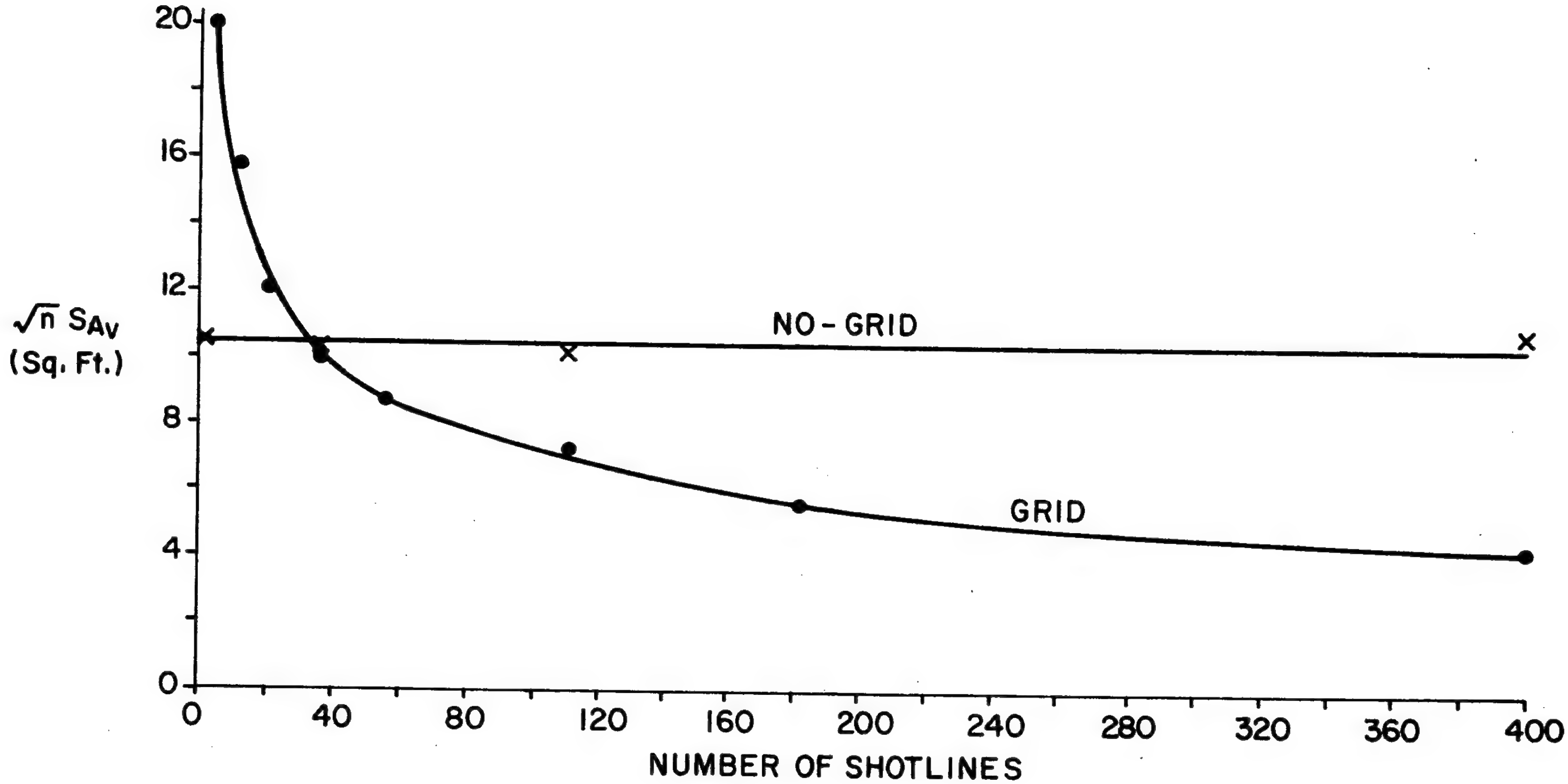


FIGURE 4. STANDARD DEVIATION TIMES SQUARE ROOT OF THE NUMBER OF SHOTLINES VERSUS NUMBER OF SHOTLINES.

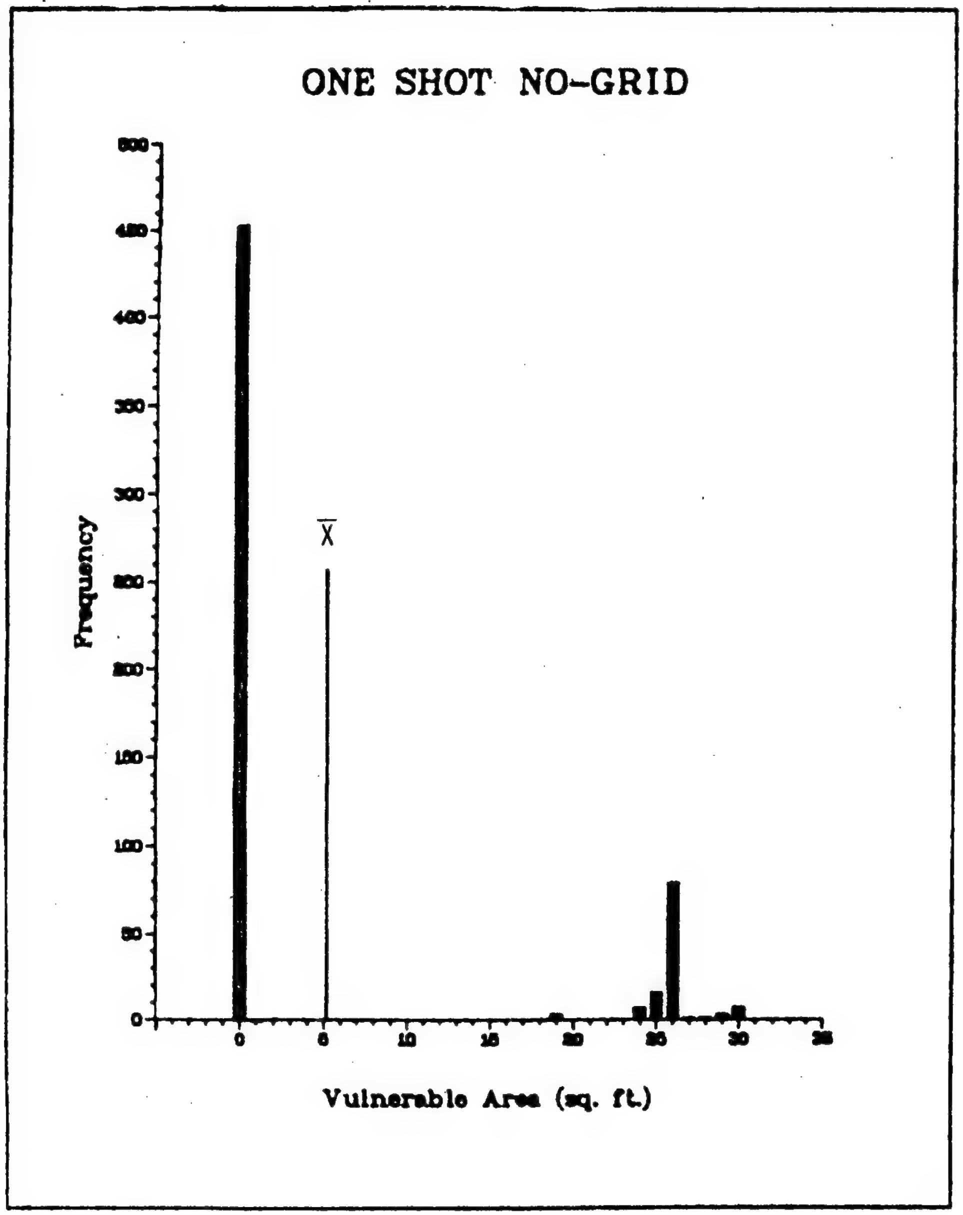
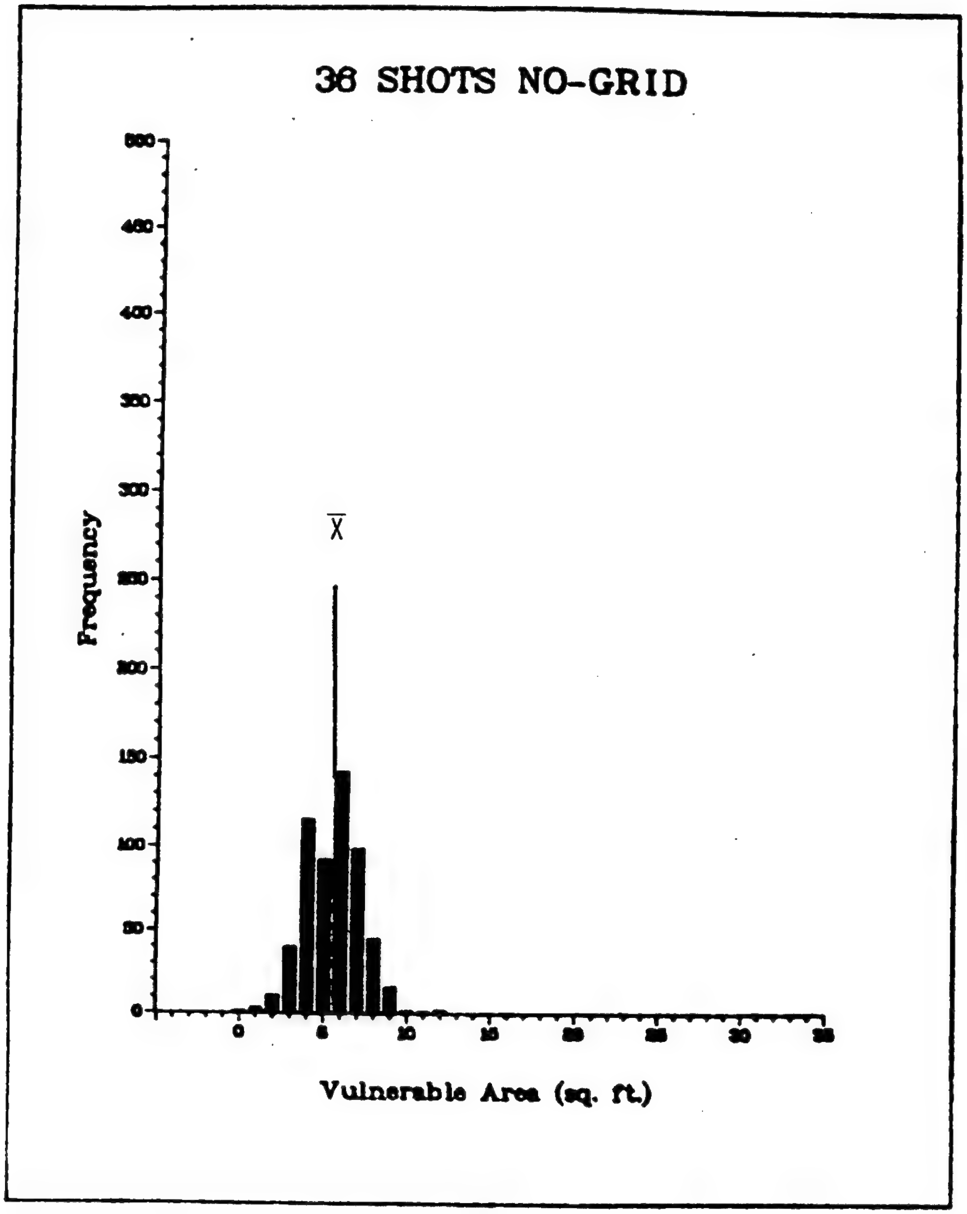


FIGURE 5. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA



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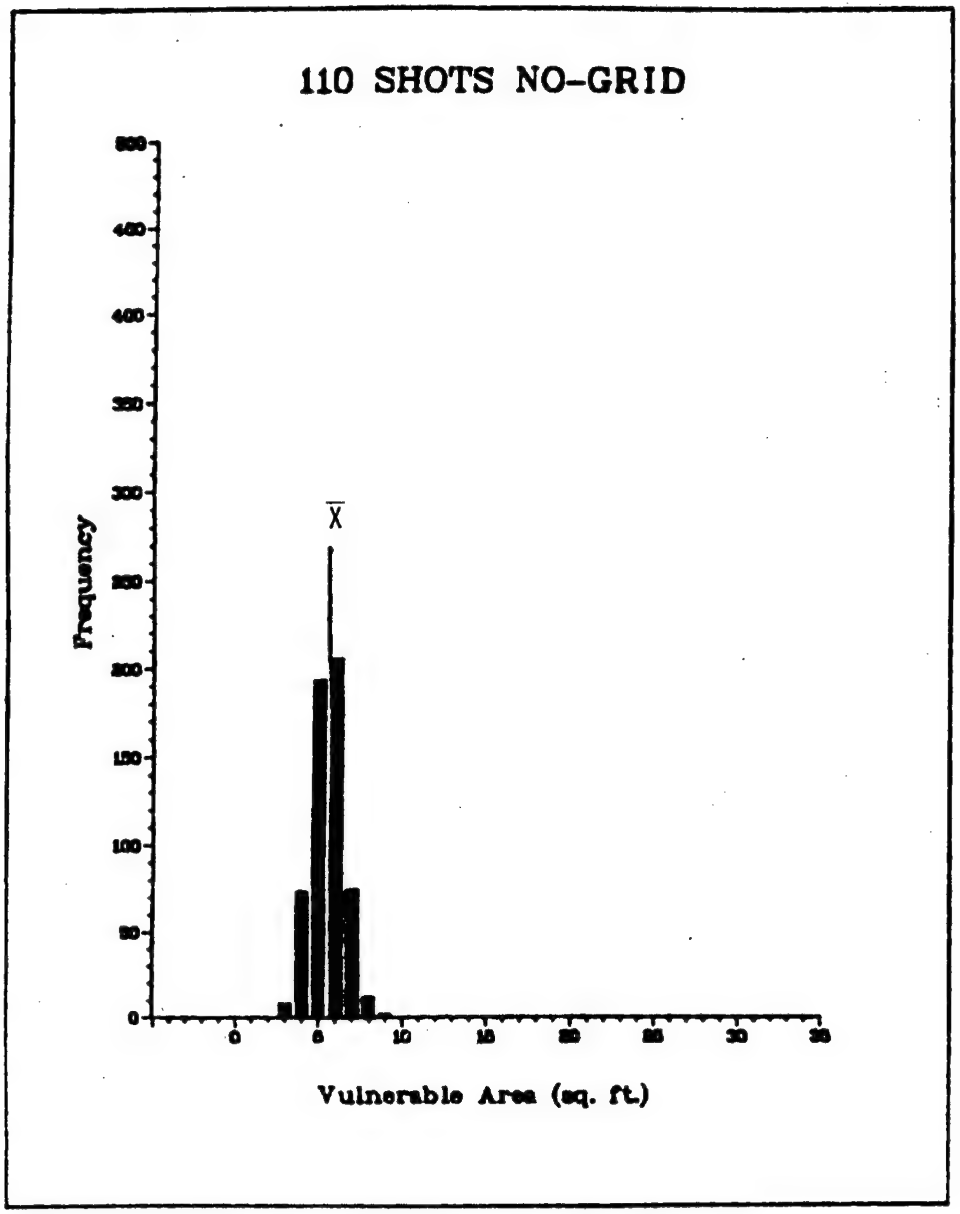

FIGURE 7. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

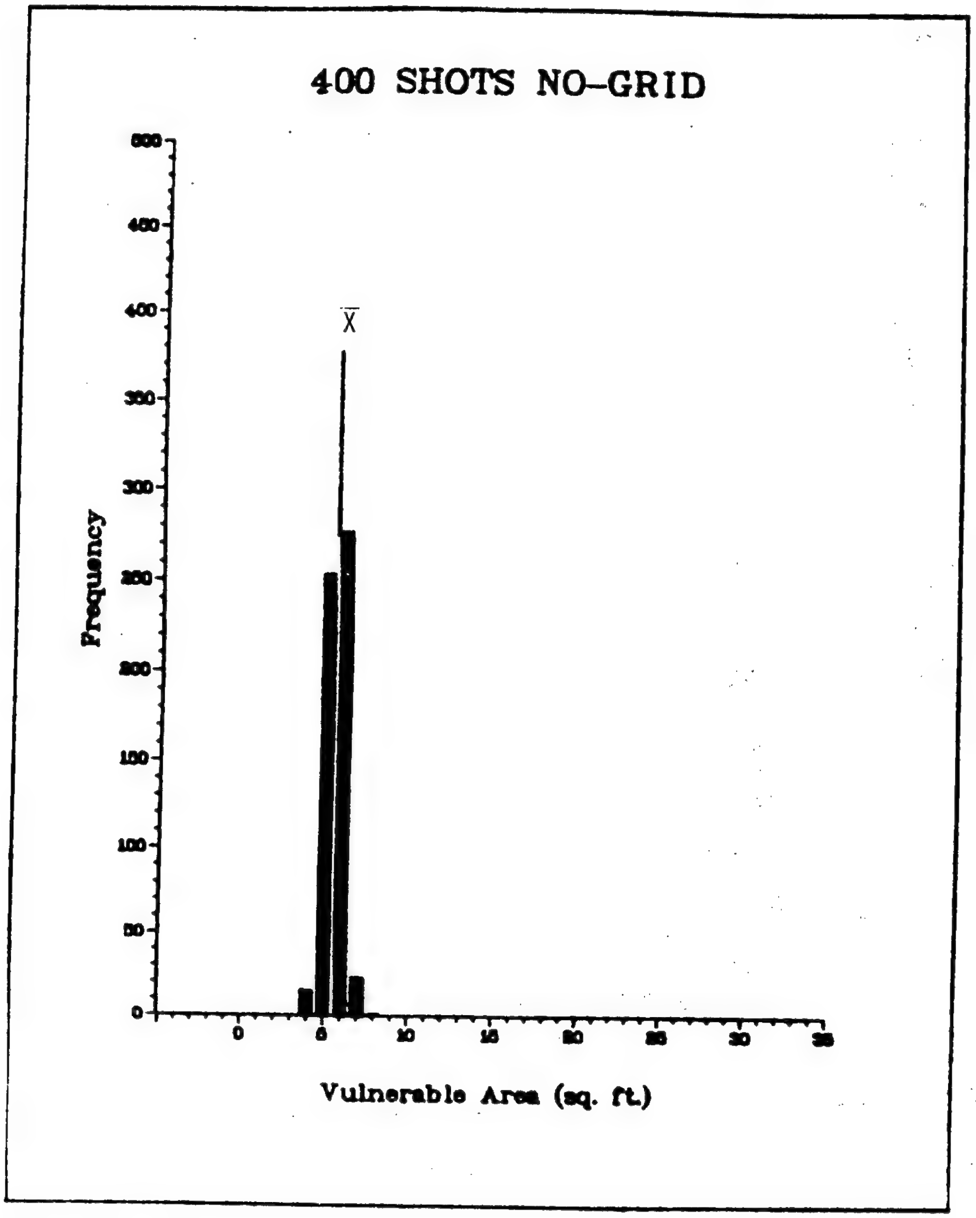

FIGURE 8. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

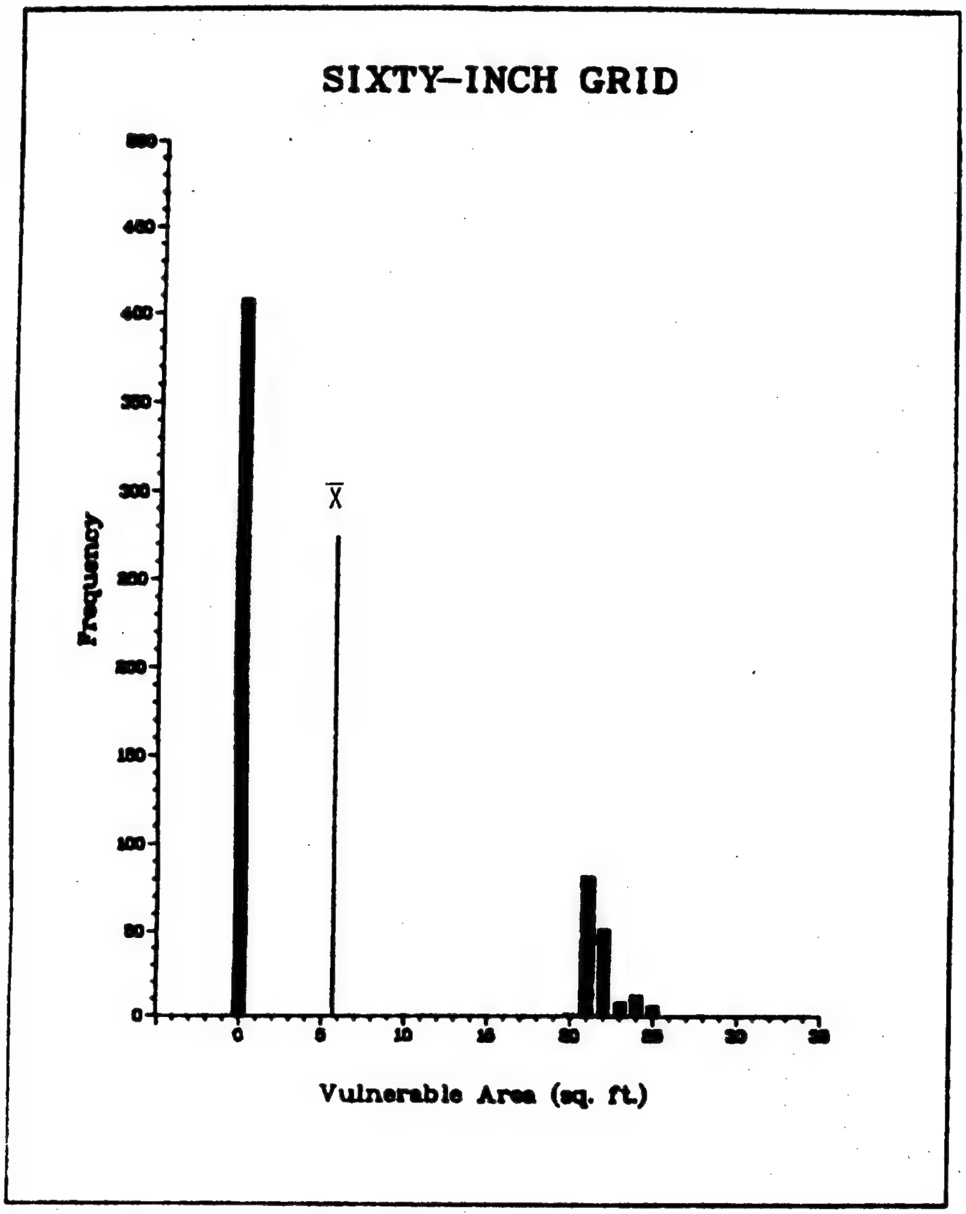

FIGURE 9. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

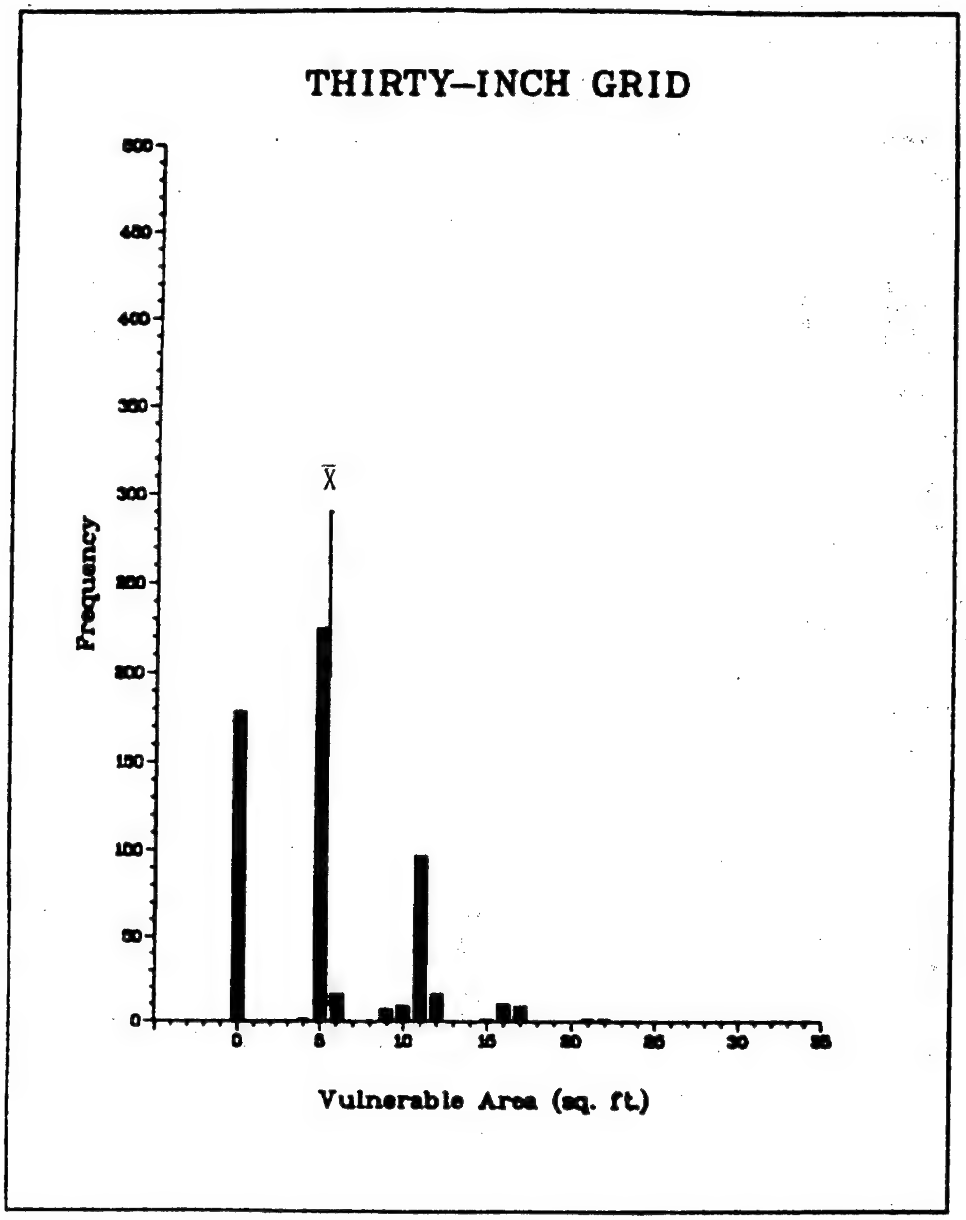

FIGURE 10. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

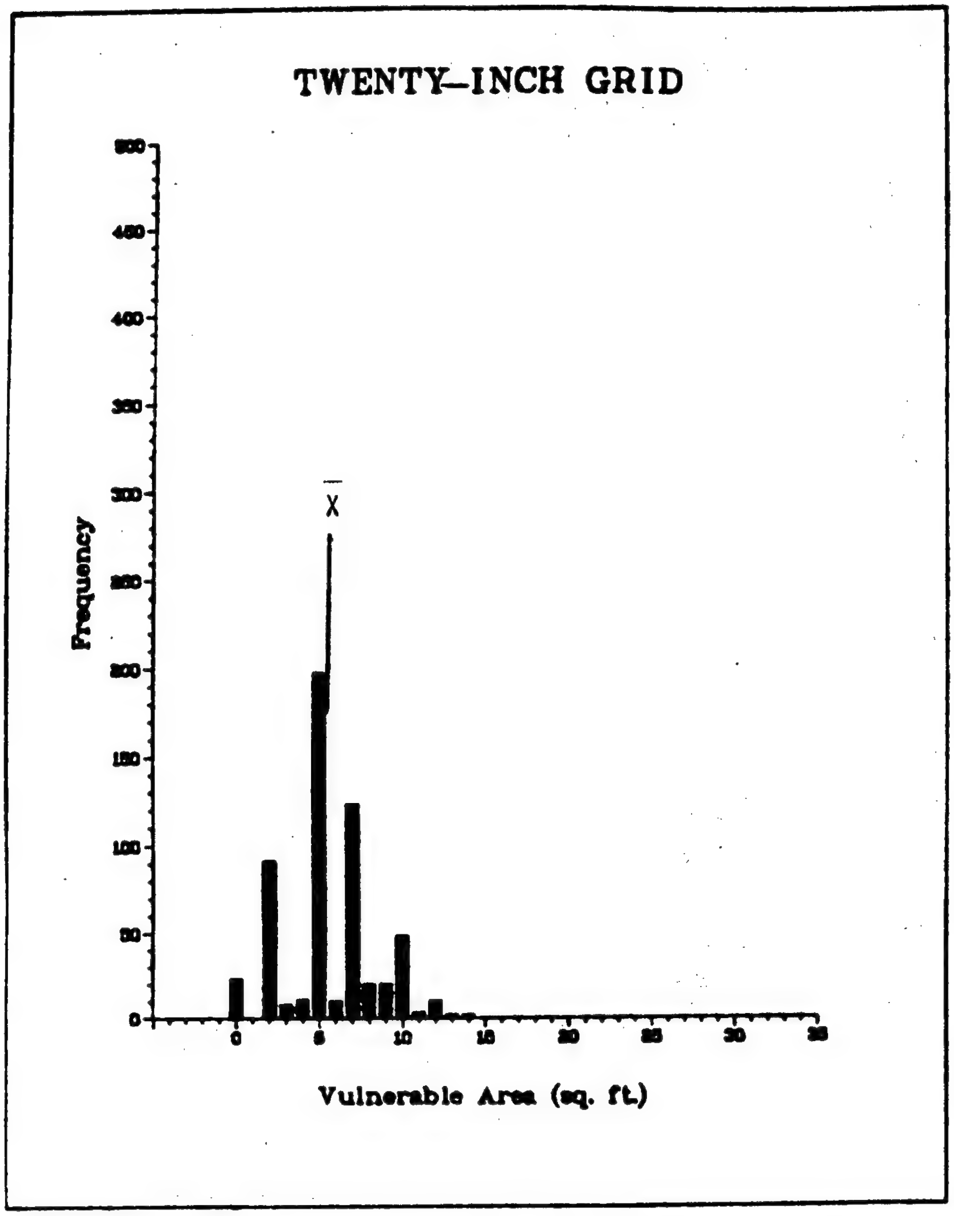

FIGURE 11. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

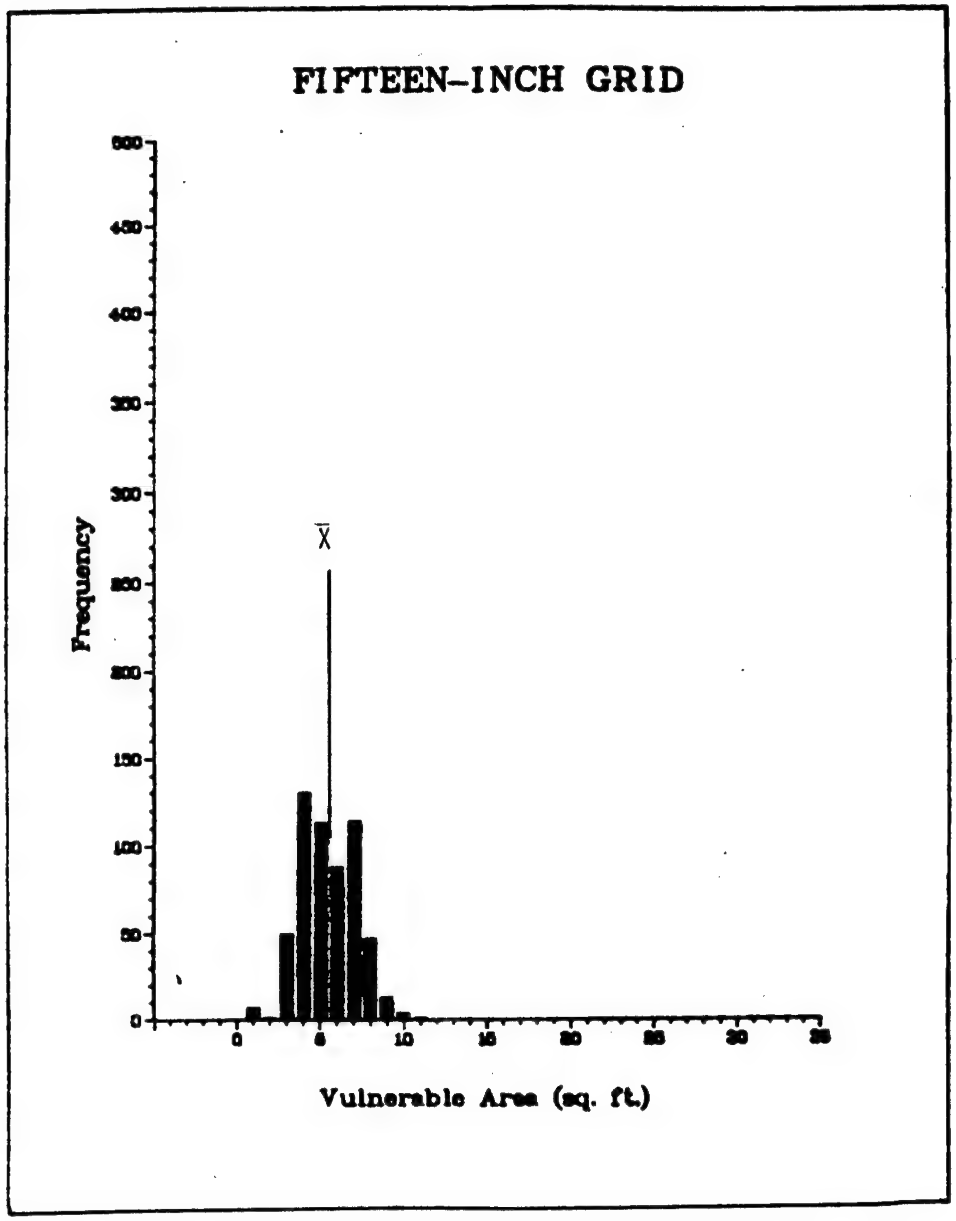

FIGURE 12. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

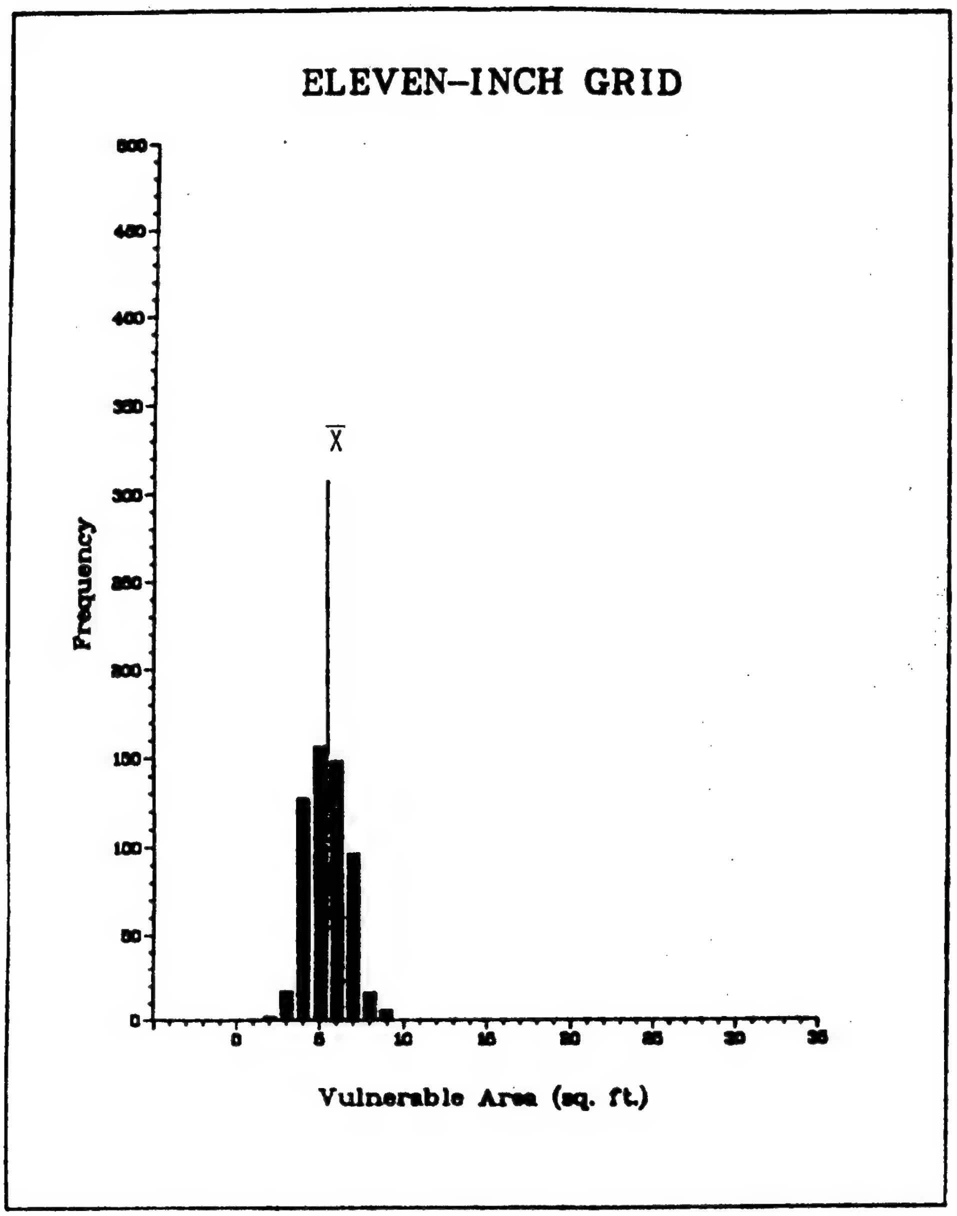

FIGURE 13. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

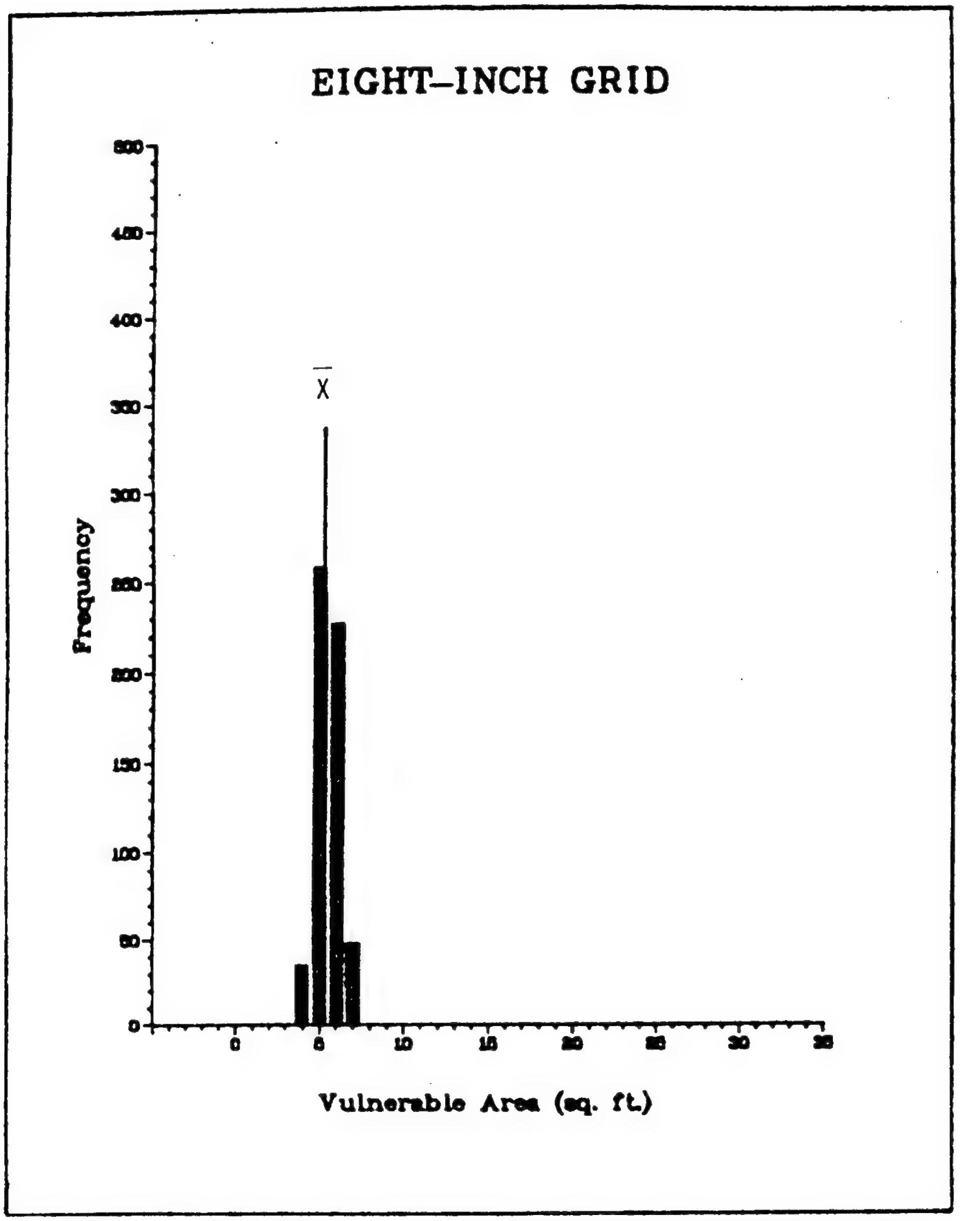

FIGURE 14. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

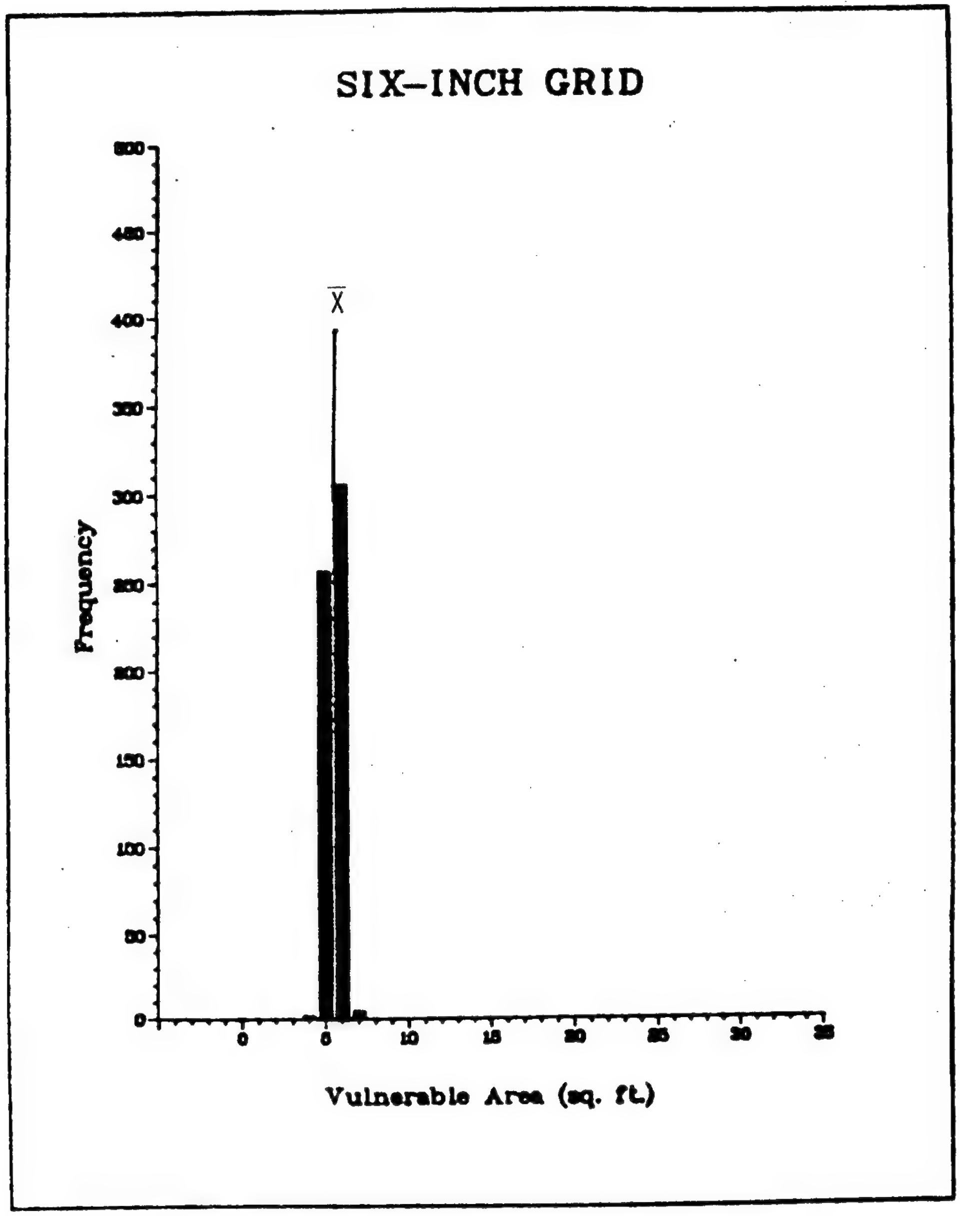

FIGURE 15. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

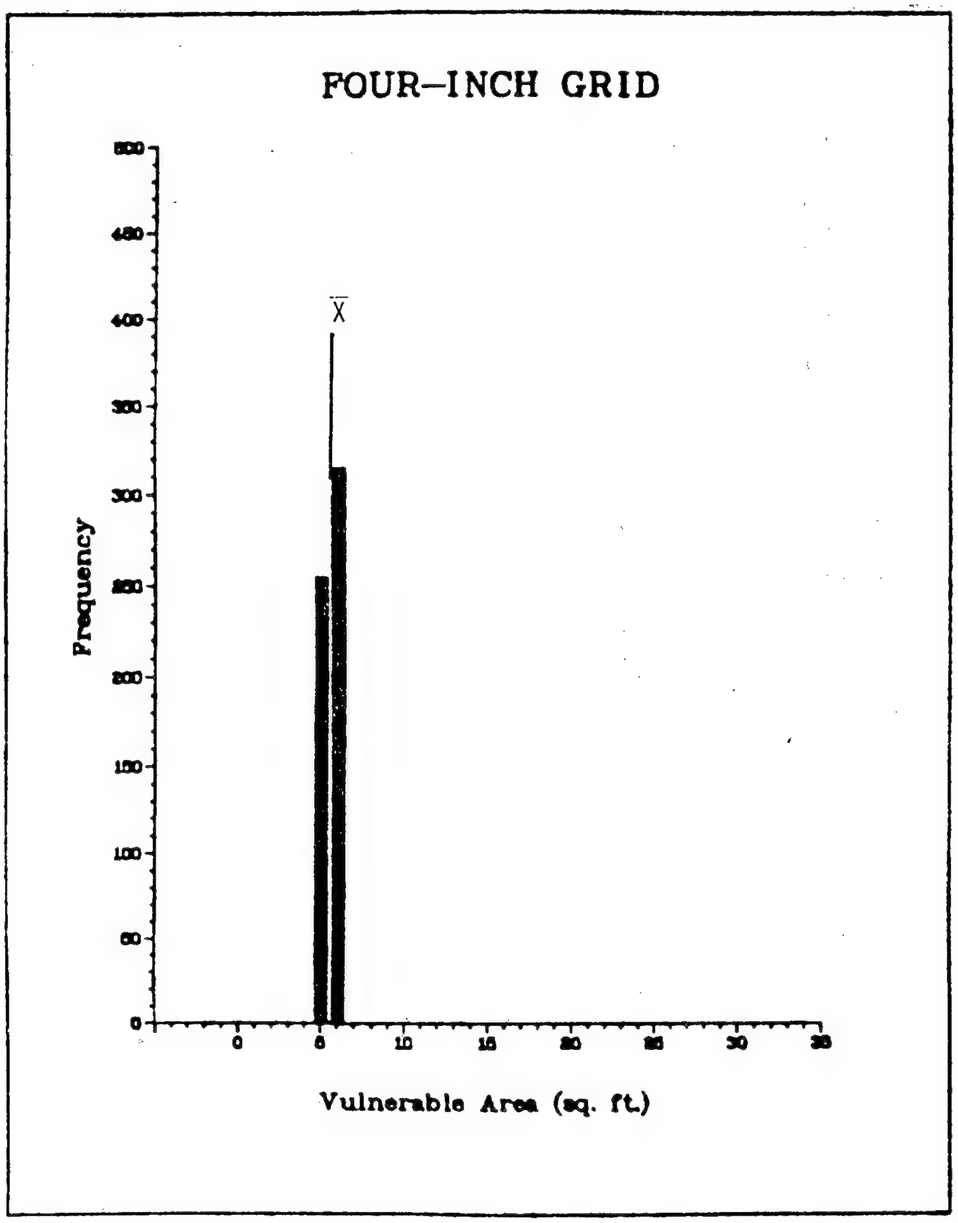

FIGURE 16. DISTRIBUTION OF ESTIMATED MEAN VULNERABLE AREA

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